LLNL-PRES-633012

The impact of background turbulence on ELMs

BOUT++
Boundary Plasma Turbulence Code

P. W. Xi[1,2], X. Q. Xu[2], P. H. Diamond[3,4]

[1]FSC and State Key Lab of Nuclear Physics & Technology, Department of Physics, Peking University, Beijing, China, 100871
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[3]WCI Center for Fusion Theory, NFRI, Daejon, R. Korea
[4]CASS and Department of Physics, UCSD, La Jolla, CA 92093-0429, USA

Presented at ITPA, Garching, Germany

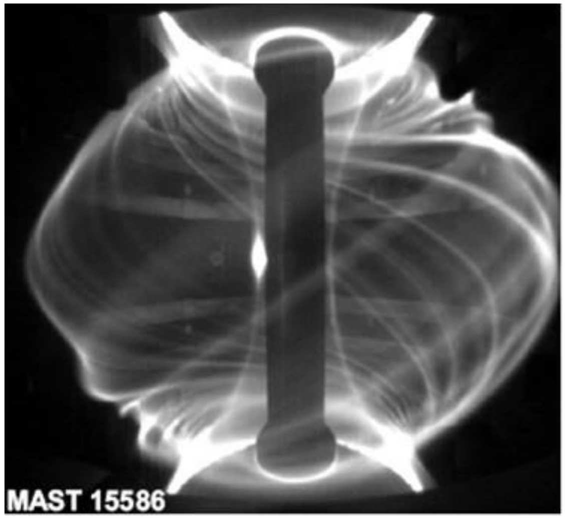
4/22/2013

This work was performed under the auspices of the U.S. DoE by LLNL under Contract DE-AC52-07NA27344 and is supported by the NSFC under Grant Nos.10935004, 11261140326. This work is also supported by the China Scholarship Committee under contract N0.2011601099.

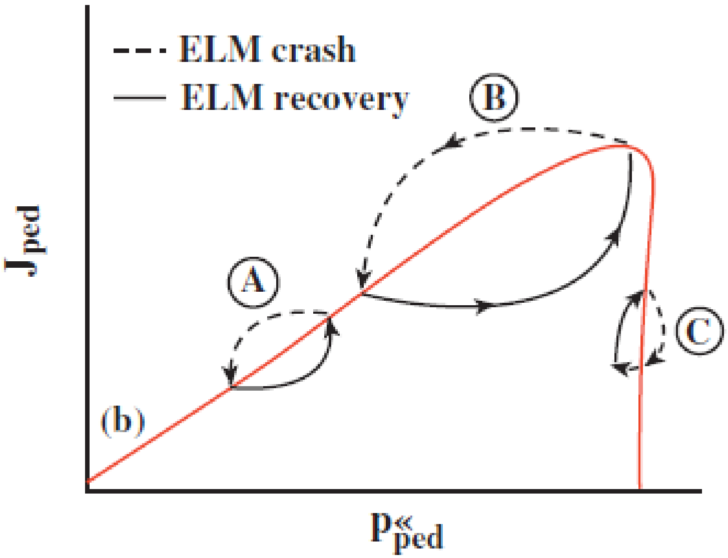
OUTLINE

1. **Introduction and motivation**
2. **Nonlinear Peeling-ballooning model for ELM**
   - Initial perturbation and self-generated peeling-ballooning turbulence
   - Shift of linear threshold
   - Nonlinear peeling-ballooning model and ELM-free H-mode regime
3. **Summary**

Background : Peeling-ballooning model for ELMs



A. Kirk, PRL **96**, 185001 (2006)



P.B. Snyder, et.al *Nucl. Fusion* **47** (2007) 961

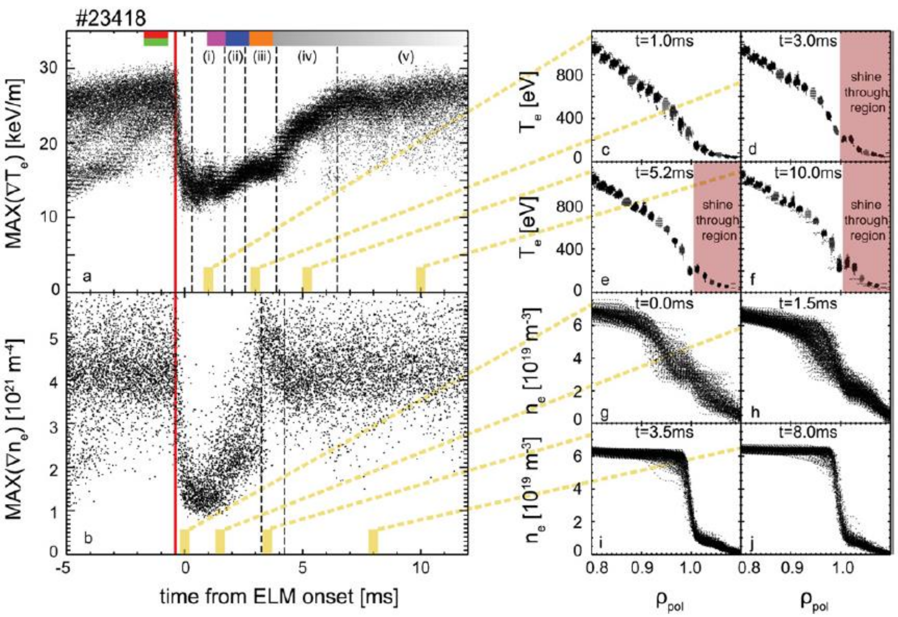
- **Peeling-ballooning model → Linear theory**
  - ✓ ELM crash is triggered by linear peeling-ballooning instability;
  - ✓ Criterion for ELM crash:

$$\gamma_{PB} > 0$$

  - ✓ Different ELMy H-mode regimes are due to different linear instability;
  - ✓ Filamentary structure is determined by linear instability;
  - ✓ Combined with KBM theory, pedestal width and height can be determined →EPED model

- **However, as nonlinear phenomenon, can ELM only depend on linear instability?**

The limitation of linear peeling-ballooning model: nonlinear phenomena needs nonlinear physics model



ASDEX Upgrade result (A.Burckhart, *Plasma Phys. Control. Fusion* **52** (2010) 105010)

To answer these questions, nonlinear ELM simulations are necessary.

- **More to answer:**
  - ? In some experiments, pedestal reach its maximum profile gradient, but no ELM crash;
  - ? Pedestal can crosses $\gamma_{PB} = 0$ boundary without ELM;
  - ? ELM crash happens at the region far away from $\gamma_{PB} = 0$ boundary;
  - ? ELM-free regimes;
  - ? Why the filamentary structure has a certain toroidal mode number.

- **BOUT++ framework**
  - ✓ 3/4/5/6 fields nonlinear model for ELM simulation
  - ✓ Shifted circular / real tokamak geometry
  - ✓ Well benchmarked with linear codes on linear growth rate

OUTLINE

1. Introduction and motivation
2. **Nonlinear Peeling-ballooning model for ELM**
   - **Initial perturbation and self-generated peeling-ballooning turbulence**
   - Shift of linear threshold
   - Nonlinear peeling-ballooning model and ELM-free H-mode regime
3. Summary

The onset of ELMs: linear or nonlinear threshold?

- **What triggers an ELM?**
  - ✓ Linear peeling-ballooning instability (peeling-ballooning model);
- **But how?**

➢ If assume nonlinear interaction not important before ELM crash: **linear threshold**

Linear phase → Nonlinear ELM crash

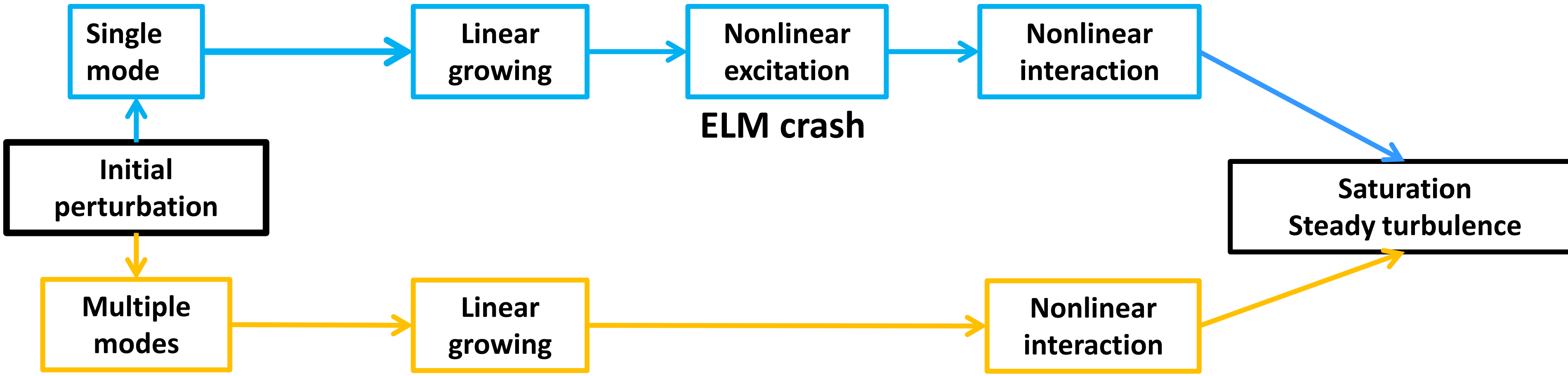
➢ Consider nonlinear interaction before the onset of ELMs:

Linear phase → Nonlinear process - - → Nonlinear ELM crash

✓ **Correct triggering process of ELM: nonlinear threshold**

Linear phase → Nonlinear process → Linear dominant phase → Nonlinear ELM crash

Initial perturbation in nonlinear simulations



Single mode: $\tilde{p}_{t=0} = A(x,y)e^{inz}$

Multiple modes: $\tilde{p}_{t=0} = \sum_n A_n(x,y)e^{inz}$

- Micro-turbulence (ITG/ETG/TEM): **only final turbulence matters**
  - Different numerical methods, different transition phases;
  - Same saturation turbulence → same physics
- ELMs: **the whole process is important**
  - **Two different understanding on the triggering of ELMs**
    - ✓ **Single mode: The triggering of ELM only depends on linear instability;**
    - ✓ **Multiple modes: The triggering of ELM also depends on nonlinear mode interaction;**

Simulation model and equilibrium

- **3-field model for nonlinear ELM simulations**
  - ✓ **Including essential physics for the onset of ELMs**

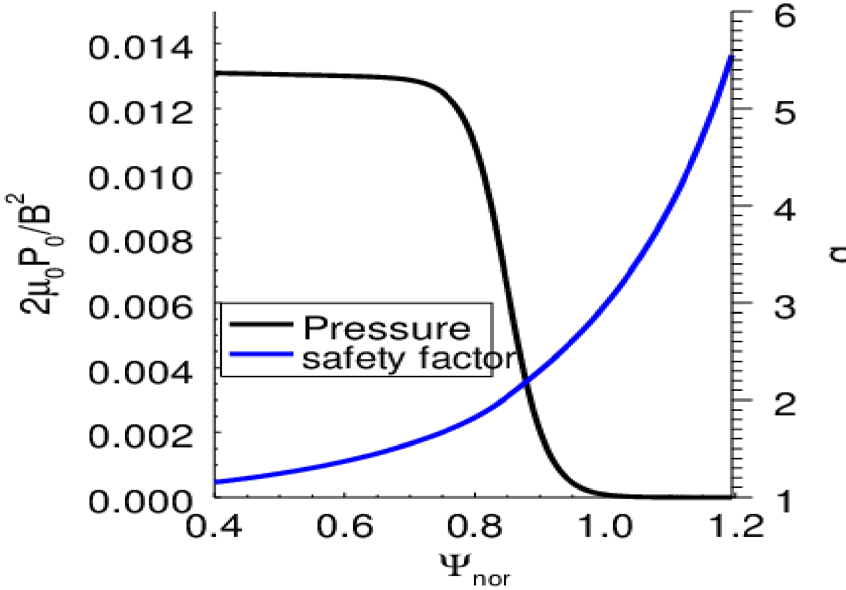
$$\frac{d\varpi}{dt} = B\nabla_{\parallel} J_{\parallel} + 2\mathbf{b}_0 \times \boldsymbol{\kappa} \cdot \nabla \tilde{P} + \mu_{i,\parallel}\partial_{\parallel}^2 \varpi$$

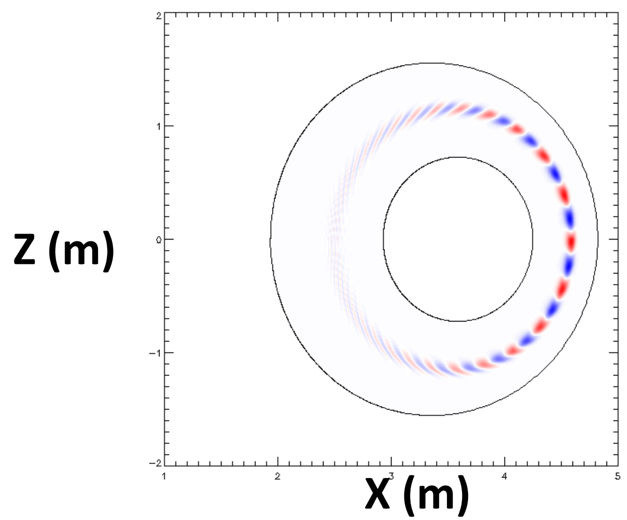
$$\frac{d\tilde{P}}{dt} + \mathbf{V}_E \cdot \nabla P_0 = 0$$

$$\frac{\partial A_{\parallel}}{\partial t} + \partial_{\parallel}\phi_T = \frac{\eta}{\mu_0}\nabla_{\perp}^2 A_{\parallel} - \frac{\eta_H}{\mu_0}\nabla_{\perp}^4 A_{\parallel}$$

$$\varpi = \frac{m_i n_0}{B}\left(\nabla_{\perp}^2 \phi + \frac{1}{en_0}\nabla_{\perp}^2 \tilde{P}_i\right)$$

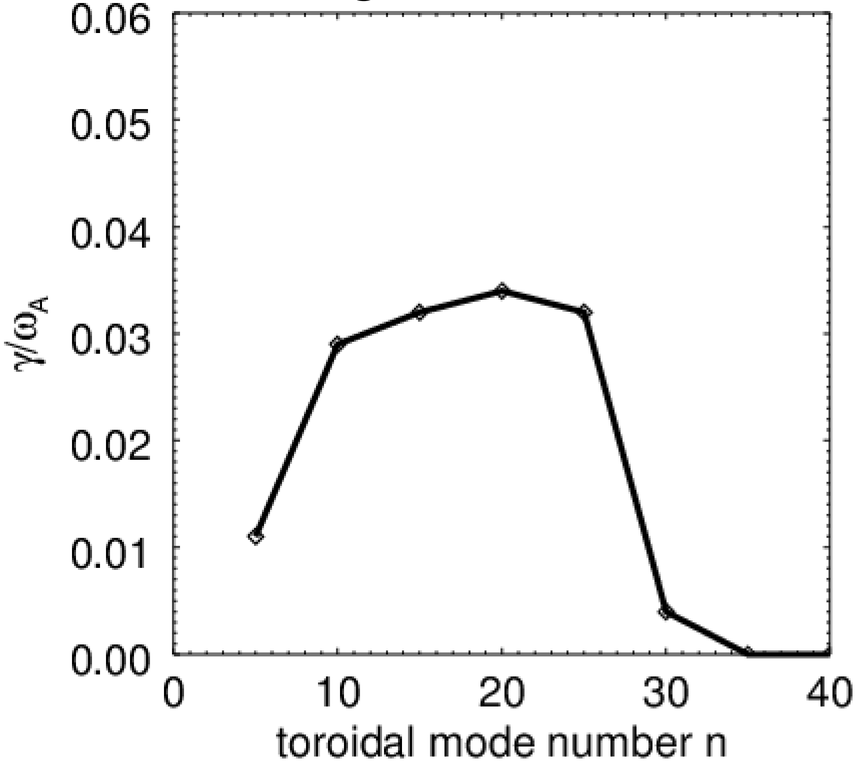
$$d/dt = \partial/\partial t + \mathbf{V}_{ET}\cdot\nabla, \mathbf{V}_{ET} = \frac{1}{B}\mathbf{b}_0 \times \nabla\phi_T, \phi_T = \phi_0 + \phi, \nabla_{\parallel} f = B\partial_{\parallel}\frac{f}{B}, \partial_{\parallel} = \partial_{\parallel}^0 + \delta\mathbf{b}\cdot\nabla, \delta\mathbf{b} = \frac{1}{B}\nabla A_{\parallel} \times \mathbf{b}_0, J_{\parallel} = J_{\parallel 0} + \tilde{J}_{\parallel}, \tilde{J}_{\parallel} = -\nabla_{\perp}^2 A_{\parallel}/\mu_0$$



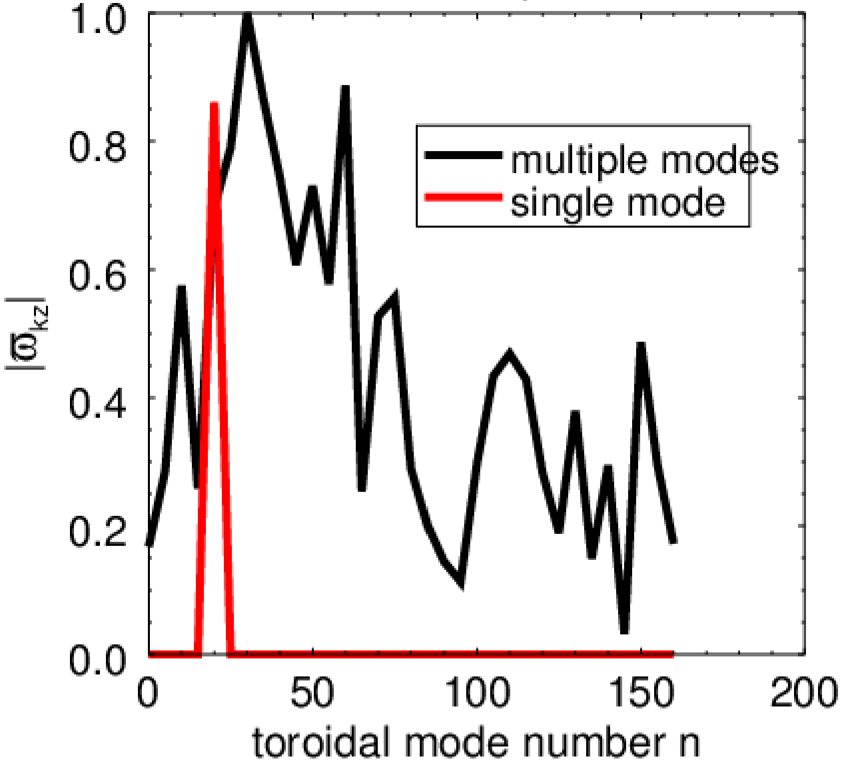


Initial perturbation: single mode and multiple modes

Linear growth rate



Initial toroidal spectrum



- **Peeling-ballooning unstable**
  - ➢ **ELM crash according to P-B model**

Single mode $\tilde{p}_s = A(x,y)e^{inz}$

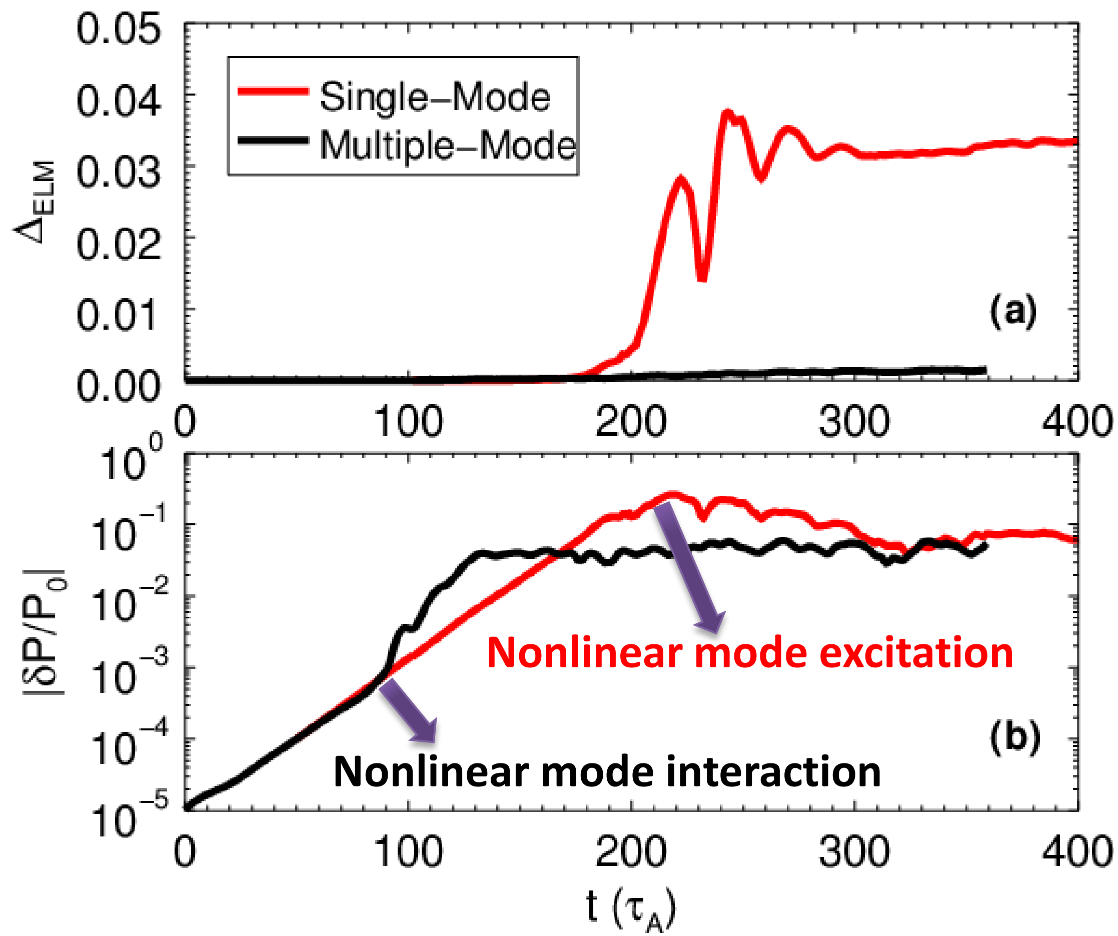
Multiple modes $\tilde{p}_m = \sum_n A_n(x,y)e^{inz}$

Single mode: ELM crash || Multiple modes: no ELM

- ELM size

$$\Delta_{ELM} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\int dx^3 (P_0 - \langle P \rangle_\zeta)}{\int dx^3 P_0}$$

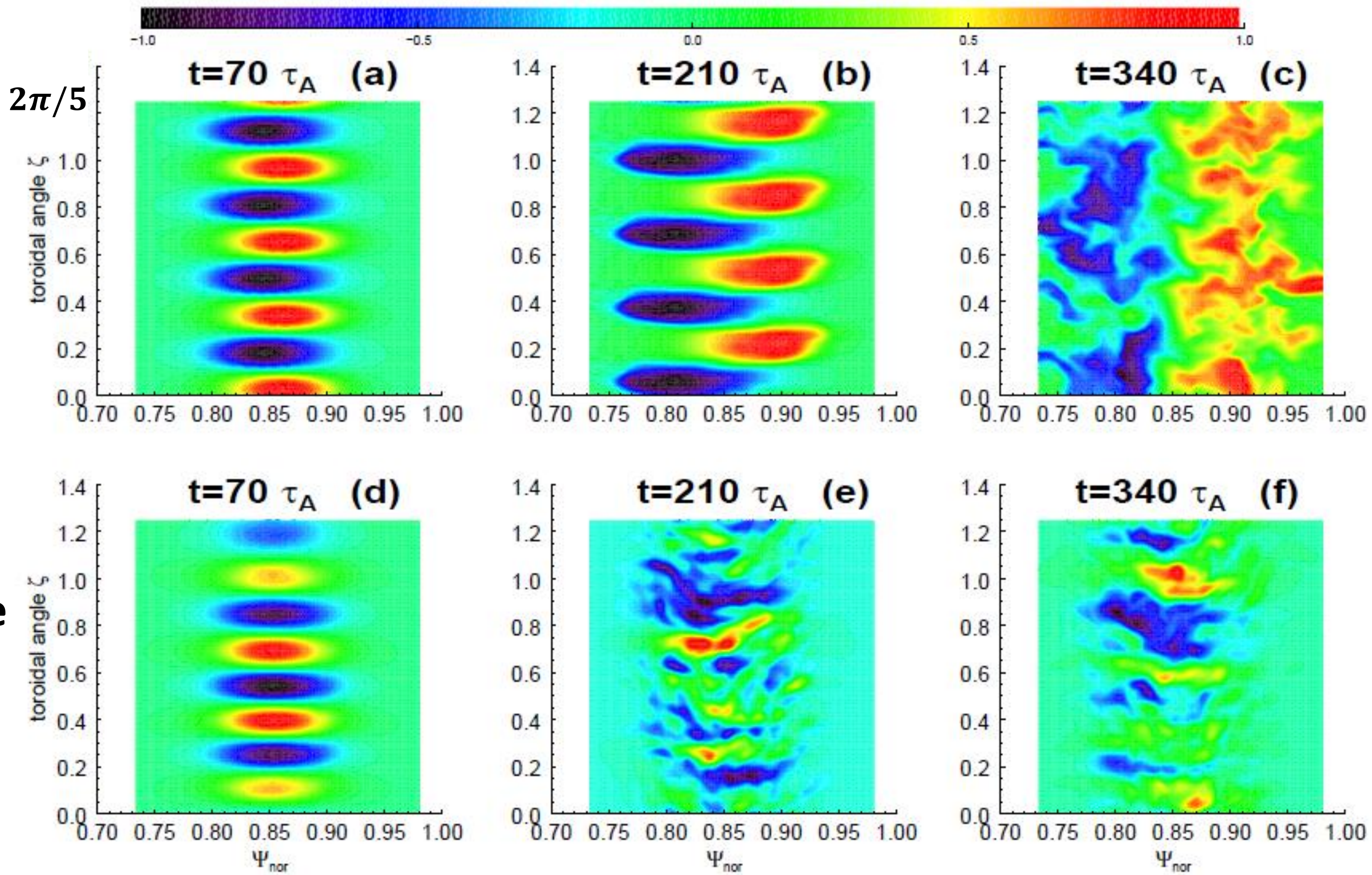
- **Single mode simulation**:
  - ✓ Keep linear growing for 200 τ_A;
  - ✓ Typical ELM crash ;
  - ✓ Consistent with P-B model ;
- **Multiple modes simulation**:
  - ➢ Linear growing stops at 100 τ_A;
  - ➢ ELM is replaced by steady turbulence transport;
  - ➢ Not consistent with P-B model



Different perturbation patterns (1/5 of the torus)

Single Mode

Multiple Mode



Linear phase | Early nonlinear phase | Late nonlinear phase

- **Single mode: Filamentary structure is generated by linear instability;**
- **Multiple modes: Linear mode structure is interrupted by nonlinear mode interaction and no filamentary structure appears**

The triggering of ELMs and generation of filamentary structure are nonlinear process, not linear process!

- **Why single mode simulation is consistent with peeling-ballooning model?**
  - Both regard the triggering of ELMs and the generation of filamentary structure as linear process;
  - Before ELM crash, nonlinear process is not considered;

- **Multiple mode simulation → Nonlinear mode interaction happens before the onset of ELMs!**
  - ✓ Nonlinear excitation needs higher amplitude than nonlinear mode interaction;
  - ✓ The generation of filamentary structure needs to overcome the interruption from nonlinear mode interaction;
  - ✓ The fluctuation status at pedestal is important to ELMs.

What is the status of fluctuation before ELMs?

Before ELM crashes, there always exists finite amplitude background turbulence

- **Micro-turbulence: ITG, ETG, TEM, KBM…**
  - Although strongly suppressed by **EXB** shearing, but no zero;

EPED

- **Perturbation from other large scale events**

  Last ELM;

  Sawtooth;

  External perturbation (heating, fueling, diagnostic)

No information Ignored

- **Initial perturbation from thermal noise**
  - Infinite small perturbation ;
  - Mixture of multiple modes rather than certain single mode;
  - **When the pedestal gets to linear unstable region, P-B instability will grow up and get to a turbulence state with finite amplitude at first**

  → **Self-generated peeling-ballooning turbulence**

Using the turbulence state generated at $t = 250\tau_A$ as the initial condition for other equilibriums

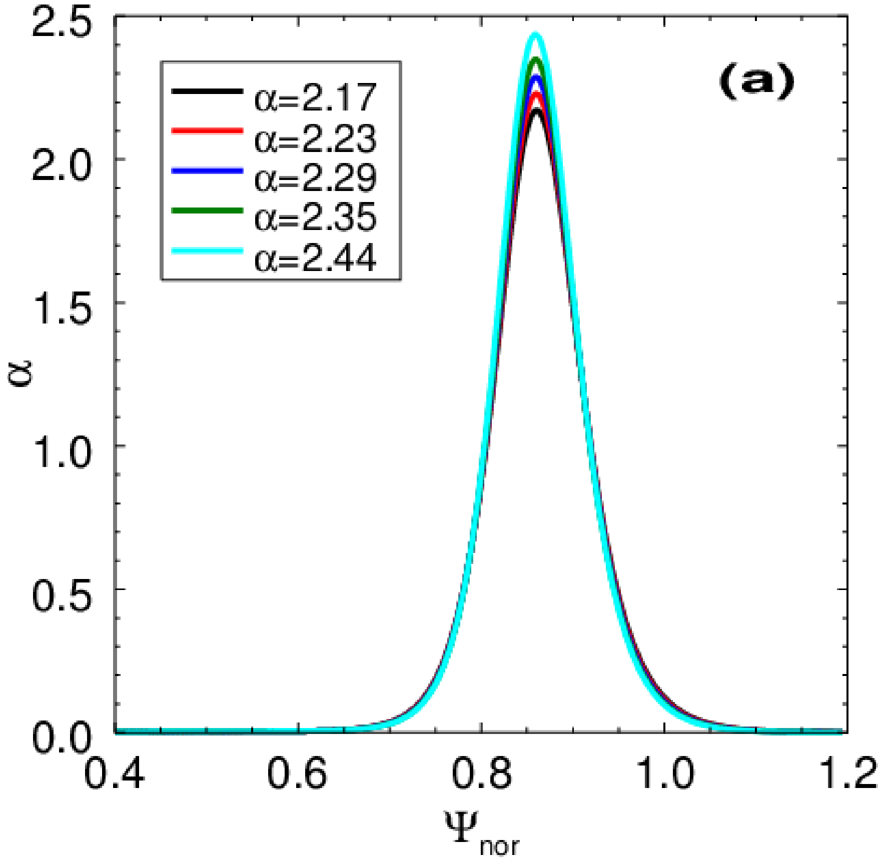
In the presence of peeling-ballooning turbulence, what is the condition for the onset of ELMs?

OUTLINE

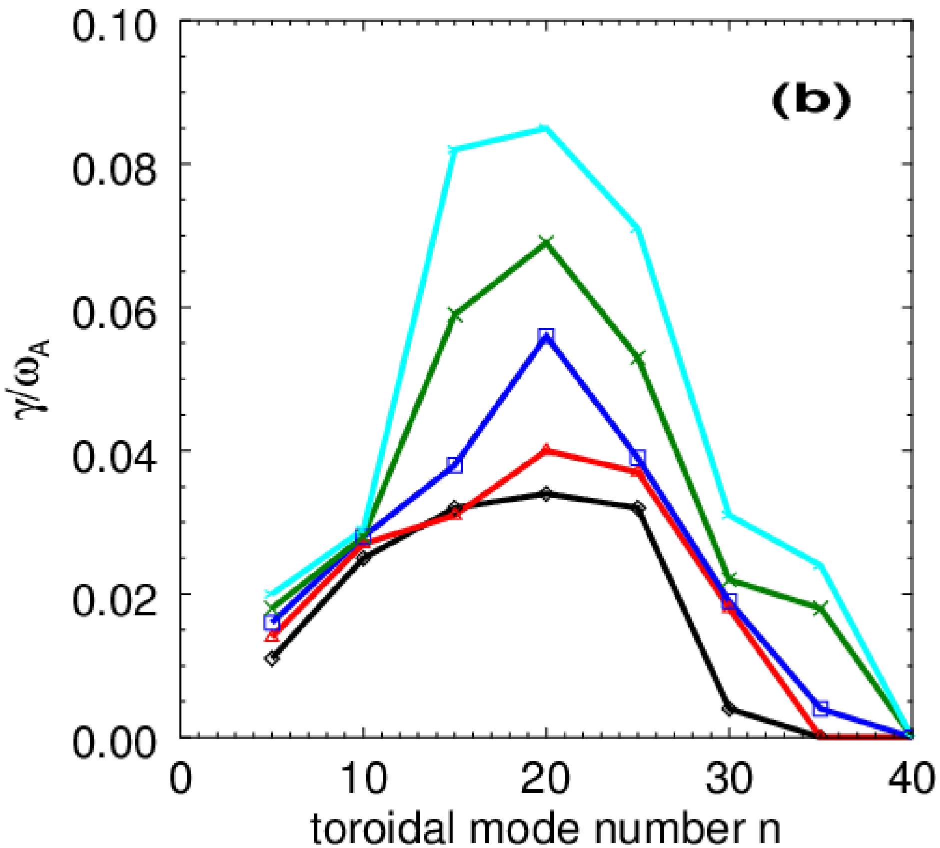
1. Introduction and motivation
2. **Nonlinear Peeling-ballooning model for ELM**
    - Initial perturbation and self-generated peeling-ballooning turbulence
    - **Shift of linear threshold**
    - Nonlinear peeling-ballooning model and ELM-free H-mode regime
3. Summary

Modeling the evolution of pedestal by increasing pressure gradient

Normalized pressure gradient



Linear growth rate



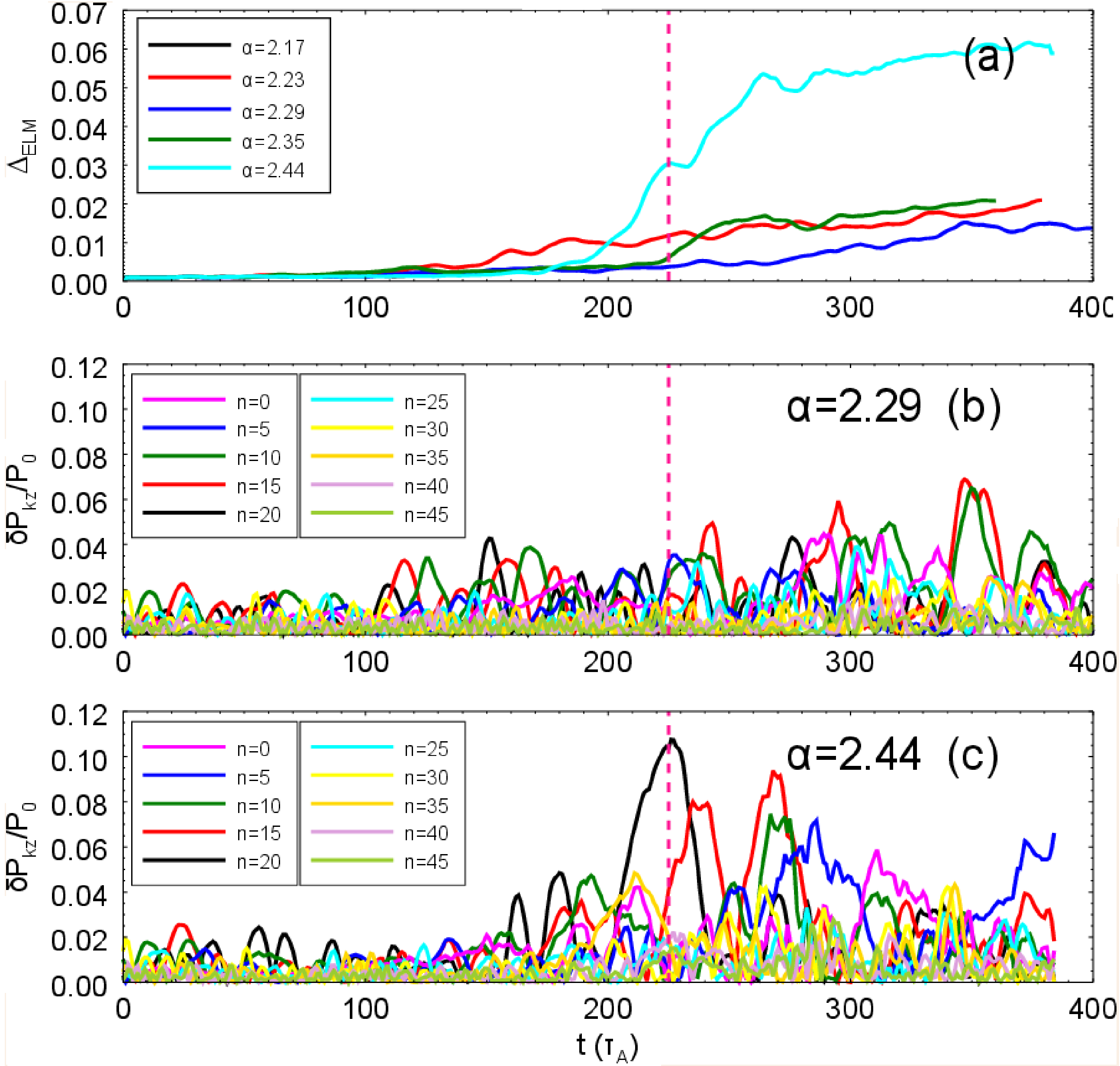
$$\boxed{\alpha = -2\mu_0 R P_0' q^2 / B^2}$$

◆ **Higher pressure gradient**

✓ Larger growth rate;

✓ Peaking up of spectrum;

With self-generated background turbulence, ELM is triggered in the case where a single mode can become dominant



- $\alpha < 2.35$
  - ➢ Turbulence transport;
  - ➢ No dominant mode;
- $\alpha = 2.44$
  - ➢ ELM crash;
  - ➢ Mode n=20 becomes dominant at first, then transferred to n=15

ELM crash starts when n=20 mode becomes dominant and this mode can sustain for about $T = 30t_A$

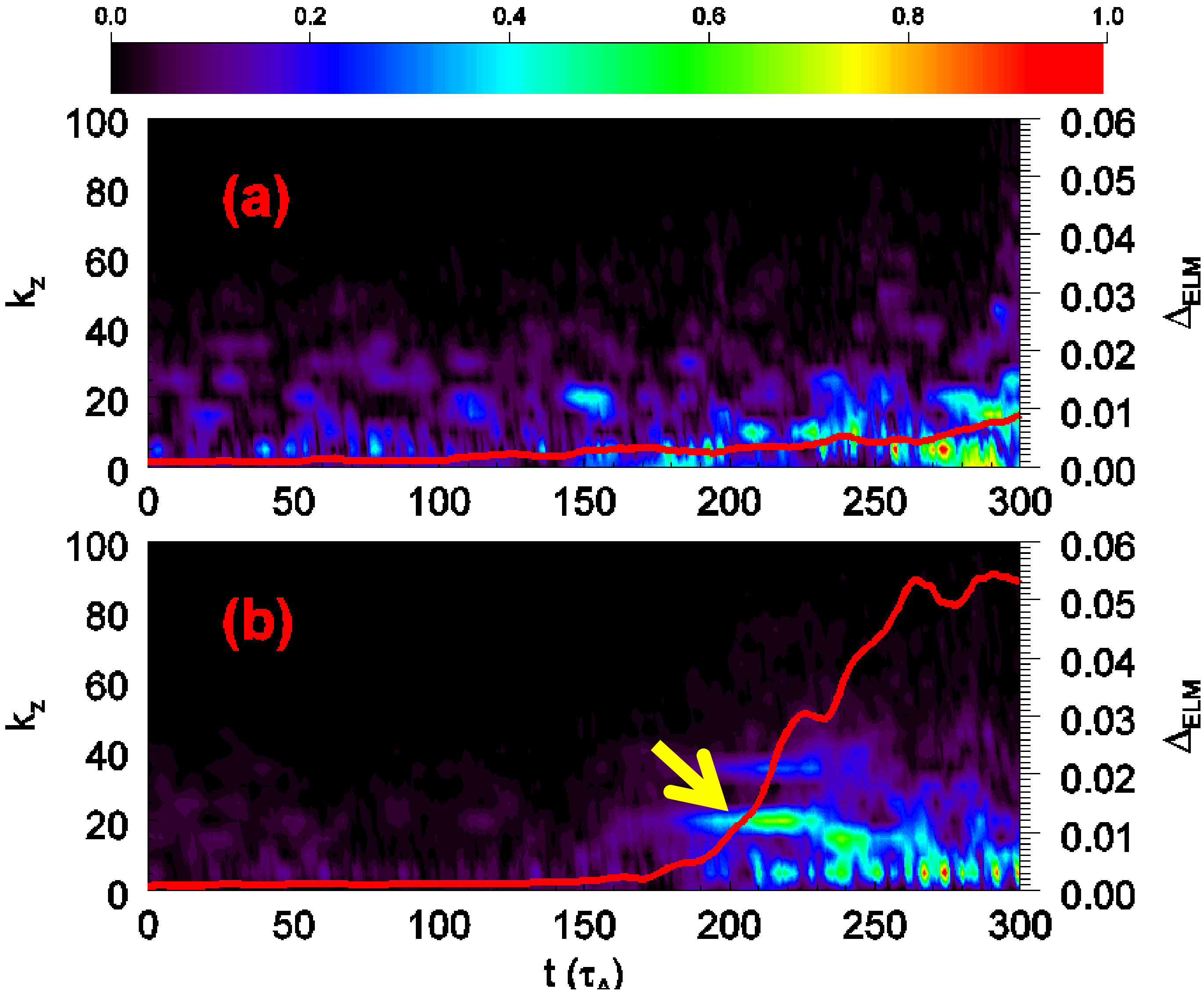
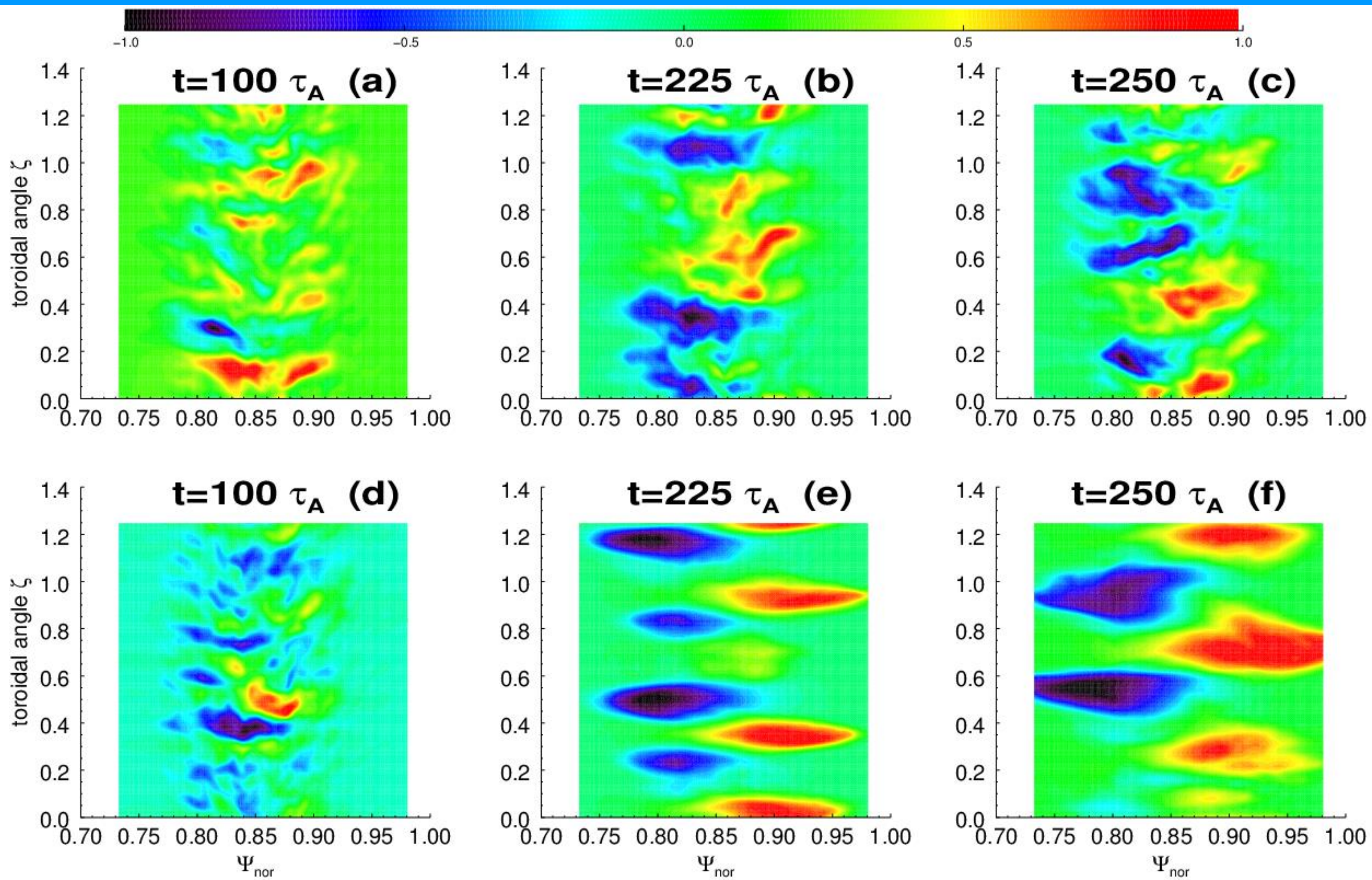


Fig. Time evolution of potential spectrum

- $\alpha = 2.29$: The life time of every mode is not long enough
- $\alpha = 2.44$: N=20 mode survives for about $30t_A$

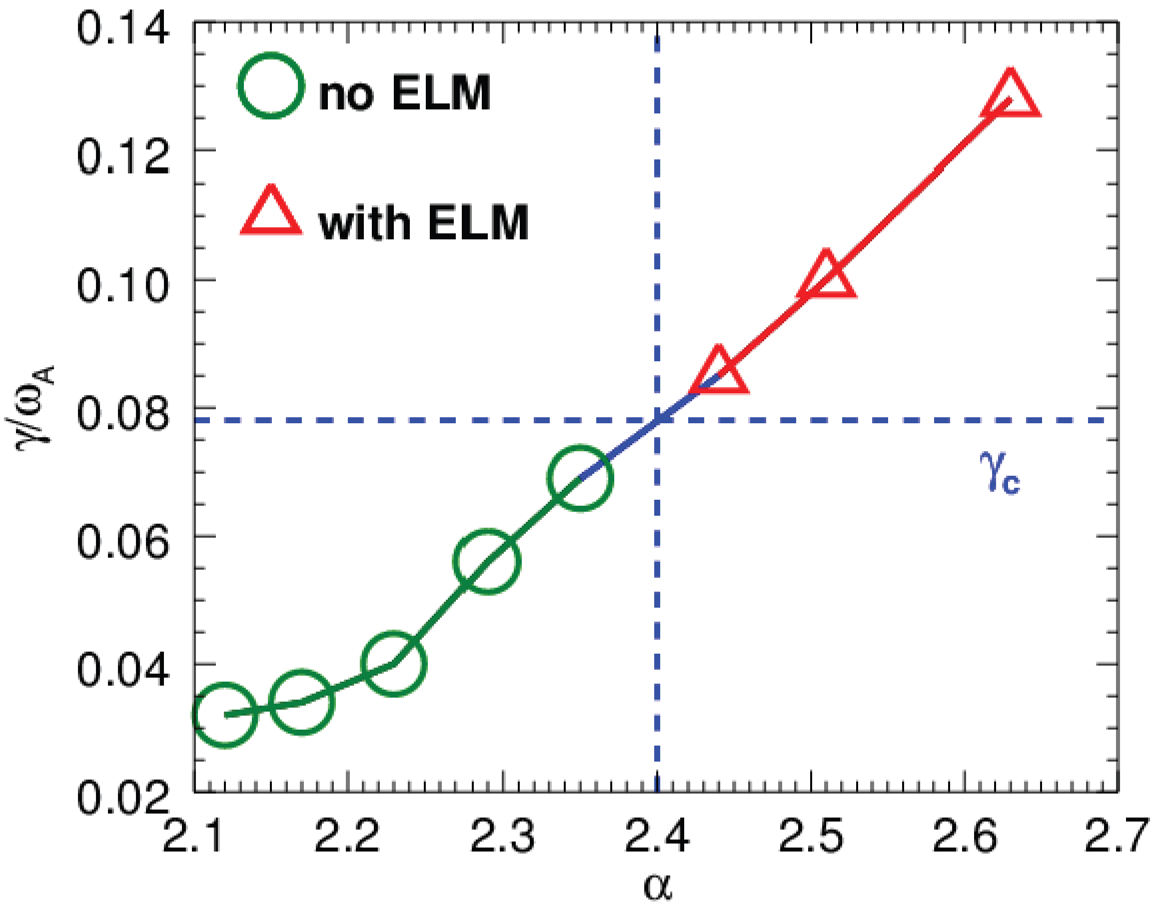
- **ELM is triggered when the fast growing mode becomes dominant for a long time**

Filamentary structure may not be the most unstable mode due to nonlinear interaction



- ❑ **Triggering ELM and the generation of filamentary structure is different process!**
  - ✓ **ELM is triggered by the most unstable mode;**
  - ✓ **Filamentary structure depends on both linear instability and nonlinear mode interaction.**

Linear criterion for the onset of ELMs $\gamma > 0$ is replaced by the new nonlinear criterion $\gamma > \gamma_c$



- γ_c **is the critical growth rate which is determined by nonlinear interaction happens in the background turbulence**

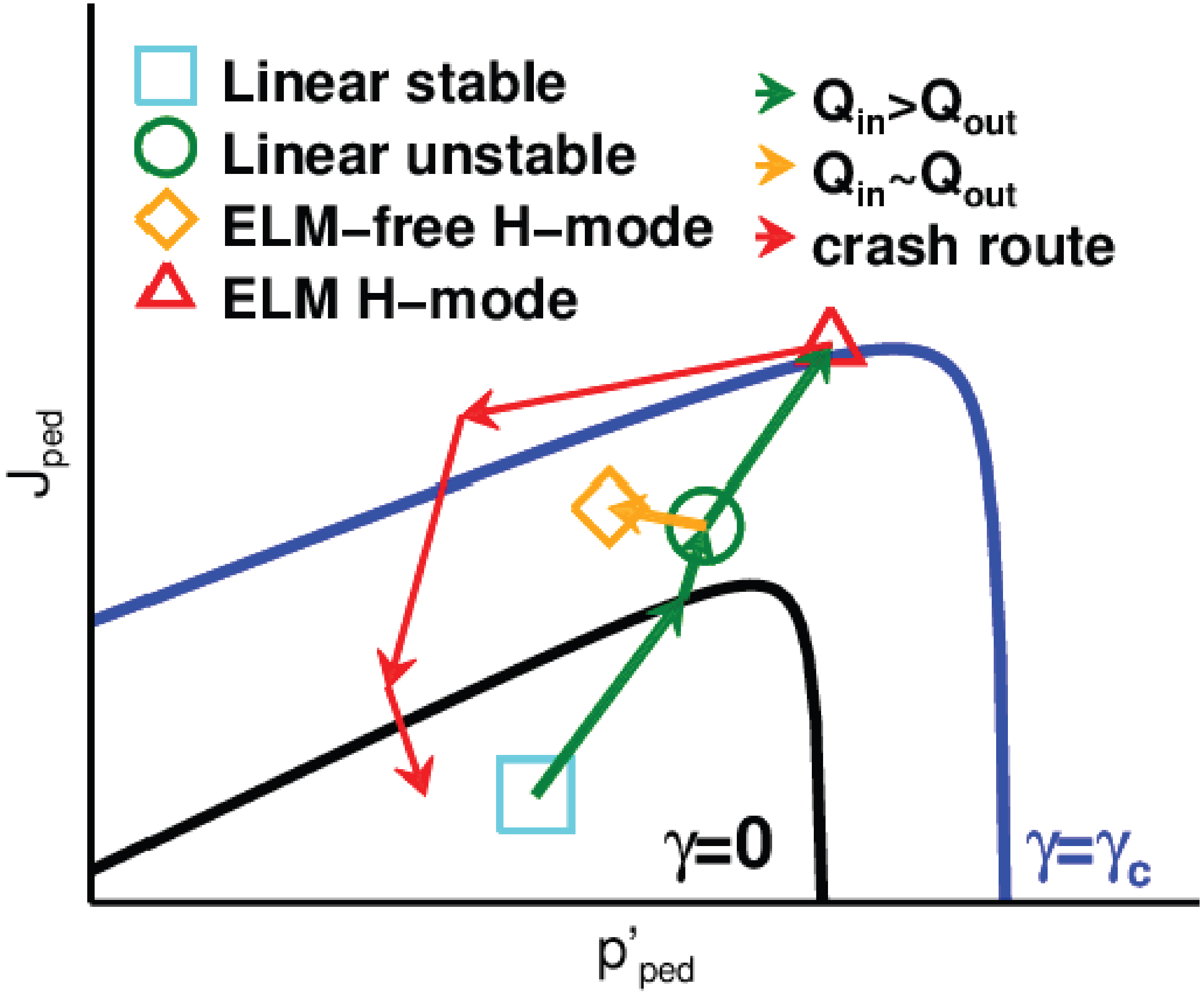
The shift of ELM threshold can be compared with the well-known Dimits shift

	Dimits shift	ELM shift
What is shifted?	Onset of Thermal transport	Onset of ELMs
What cause the shift	Zonal flow	Background turbulence
Linear instability	ITG mode	Peeling-ballooning mode
Linear criterion	$\gamma_{\mathrm{ITG}} > 0$	$\gamma_{\mathrm{PB}} > 0$
Nonlinear criterion	$\gamma_{\mathrm{ITG}} > \gamma_{\mathrm{Dimits}}$	$\gamma_{\mathrm{PB}} > \gamma_{\mathrm{c}}$
Basic idea	Nonlinear process changes linear criterion	

OUTLINE

1. Introduction and motivation
2. **Nonlinear Peeling-ballooning model for ELM**
   - Initial perturbation and self-generated peeling-ballooning turbulence
   - Shift of linear threshold
   - **Nonlinear peeling-ballooning model and ELM-free H-mode regime**
3. Summary

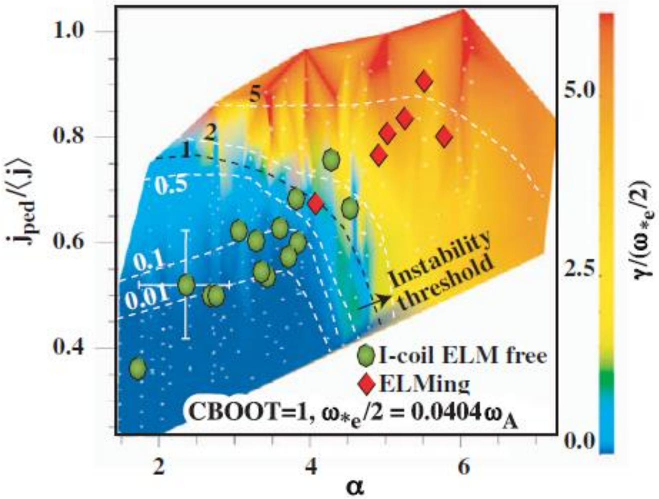
Nonlinear Peeling-ballooning model for ELM

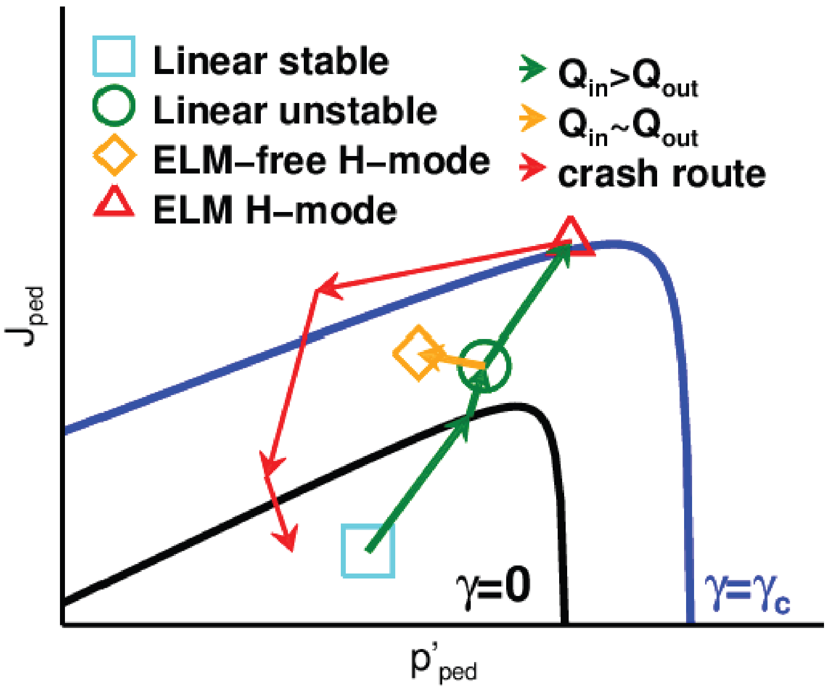


- $\gamma < 0$:
  Linear stable region
- $0 < \gamma < \gamma_c$:
  Turbulence region (Possible ELM-free regime)
- $\gamma > \gamma_c$:
  ELMy region

✓ **Different ELMy regimes depend on both linear instability and the turbulence state at the pedestal.**

Nonlinear peeling-ballooning model provides a possibility to explain those unknown questions in linear peeling-ballooning mode

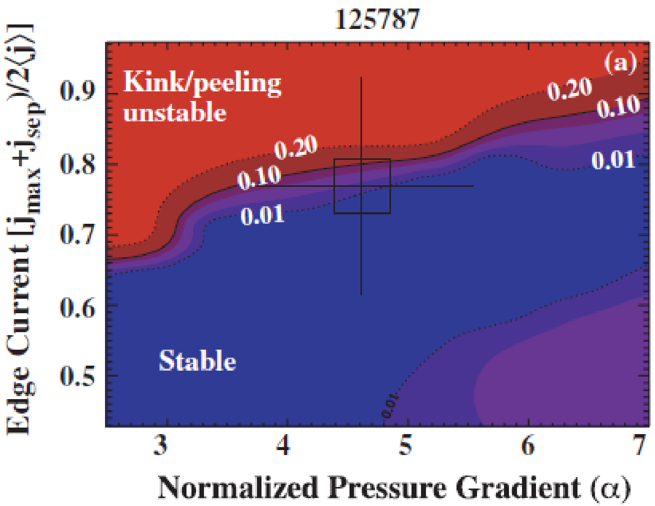




- More to answer:
  - ? In some experiments, pedestal reach its maximum profile gradient, but no ELM crash; **(turbulence delay the formation of dominant structure)**
  - ? Pedestal can crosses $\gamma_{PB} = 0$ boundary without ELM; **(ELM shift)**
  - ? ELM crash happens at the region far away from $\gamma_{PB} = 0$ boundary; **(ELM shift)**
  - ? ELM-free regimes; **(enhanced turbulence transport balances heating)**
  - ? Why the filamentary structure has a certain toroidal mode number? **(A dominant structure is necessary to trigger ELM)**

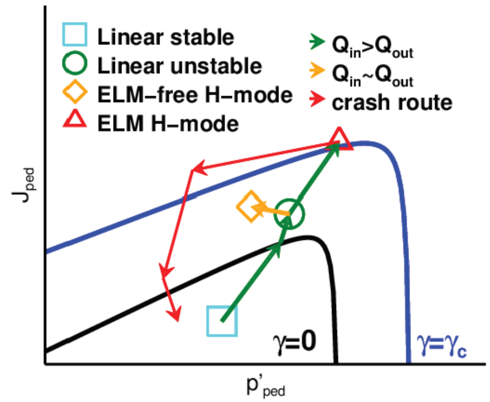
Validation of nonlinear peeling-ballooning model

- To distinguish with linear theory, more accurate measure of pedestal profiles may be necessary.
- Change the onset of ELMs by controlling edge turbulence
  - Keep profile fixed → linear instability does not change;
  - use external methods to change turbulence → γ_c changes;



P.B. Snyder, et.al *Nucl. Fusion* **47** (2007) 961

- Compare correlation time with linear growth rate;
- Compare toroidal mode number of filamentary structure with simulations
- Calculation of γ_c for real discharge
  - Real geometry with separatrix;
  - More accurate physics equations
    → 6-field equations;



Collaborations from experimentalists are more than welcome!

Open questions

- **Analytical expression for γ_c?**
  - Sharpness of spectrum;
  - Strength of mode interaction;

- **How does a n=5 mode excite the n=6 mode (non-harmonics)?**
  - Physics: 3-wave interaction, parametric instability
    - ✓ Need thermal noise;
  - Numerical: If the simulation is perfect (no numerical noise), this is impossible?
  - **Numerical noise plays the same role like thermal noise?**

Summary

- Once pedestal becomes linearly unstable, the self-generated turbulence appears at first;
- ELM is triggered when the fast growing mode becomes dominant for enough time period;
- Filamentary structure can be different from the most unstable mode due to nonlinear mode interaction;
- ELM crash is determined by the nonlinear threshold $\gamma > \gamma_c$;
- Different ELM regimes are determined by linear instability and background turbulence state;
- Nonlinear peeling-ballooning model naturally implies the existing of ELM-free regime.